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TORSIONAL SEISMIC RESPONSE OF STEEL FRAME SPECIMEN WITH ECCENTRICITY

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SUMMARY

Torsional response can destructively affect the seismic capacity of structures. Many damaged buildings due to torsional vibration were observed after sever earthquakes. However, it cannot be said that the mechanism of the damage due to the torsional vibration had been clearly investigated. The main purpose of this study is to reproduce the torsional response with the pseudo dynamic test method. The experiments on some specimens that had different eccentric ratios were carried out by the pseudo dynamic test and shaking table test method. Furthermore, the analytical studies verified those test results. The test results explain that the pseudo dynamic test can adequately reproduce the response of structure with eccentricity. The eccentricity has not an effect on the maximum response displacement at the center of gravity, but the maximum rotational angle was sensitive to the value of them. The maximum rotational response and displacement response had a correlation, which was almost linear in the results obtained from this study.

INTRODUCTION

There have been many buildings damaged due to torsional response during severe earthquakes. However, it cannot be said that the mechanism of the damage due to the torsional response has been clearly investigated. One of the main purposes of this study is to reproduce the torsional response of structures with eccentricity by the pseudo dynamic (hereinafter referred to as PSD) test, and to investigate the mechanism of the damage due to the torsional vibration. In order to verify the validity of the PSD test, the shaking table tests were also conducted [1]. Furthermore, the analytical studies verified those test results [2]. This paper presents the outlines of earthquake response tests and the outcomes from the experimental and analytical studies.

OUTLINES OF TESTS

Specimen

The specimens were one-span, one-bay and two-story steel structures as shown in Figure 1. Rigid slabs made of reinforced concrete provided the inertia force for the shaking table tests, and were used as the loading beam for the PSD test. The weight of each slab was 76.9kN for the first floor and 78.0kN for the second floor. The eccentricity was provided only on the first story by adjusting column positions as shown in Figure 1 a). Two of four columns were located closer to the center of the slab than others. The natural

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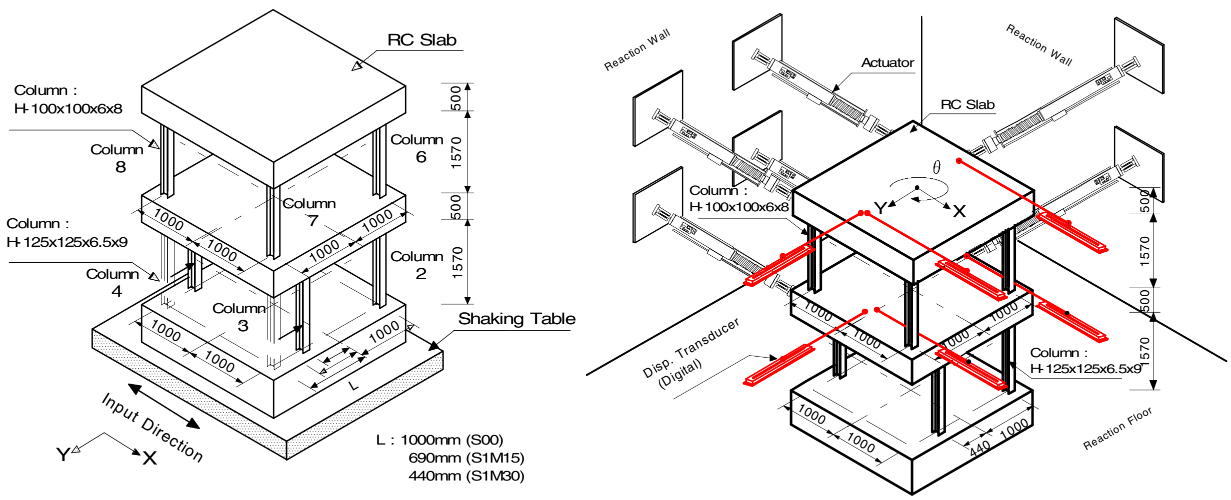
period of the specimens need to be nearly the same to neglect the effects of the frequency characteristics of the input motion. However, it is not easy to provide structures with various stiffness eccentricities that have the same natural period. Therefore, the method of adjustment of column positions on the first story mentioned above was adopted for the test in order to make the natural periods of test structures almost constant.

H-Shaped steel was used for columns (H-125x125x6.5x9 for the first story and H-100x100x6x8 for the second story). The clear height of column between top and bottom base plates was 1,500mm as shown in Figure 2. Table 1 presents material properties and Table 2 shows the strength of column, the story shear and the story shear coefficients. The story shear coefficient for the first story was 1.43 and 1.85 for the second story.



a) Shaking Table Test **b) Pseudo Dynamic Test**

Figure 1 Setup of Specimen

Table 1 Material Test Results

	H-125x125 (for First story)	H-100x100 (for Second story)
Yield Strength (N/mm^2)	304.4/301.7	347.8/340.1
Tensile Strength (N/mm^2)	431.9/435.5	475.6/473.6
Strain Fracture (%)	26.4/27.3	25.8/25.5

Left-side value is for flange, right-side value for web

Table 2 Strength of Specimen

	Yielding Moment (kN·m)	Story Shear Force at Yielding (kN)
First story	41.4/14.3 [2.9]	220.8/76.3 (1.43)
Second story	26.6/9.3 [2.9]	141.9/49.5 (1.85)

Left-side value is for X Direction, right-side value for Y Direction
[ ] : the ratio of yielding moment on X Direction to Y Direction
( ) : Story Shear Coefficient

Test parameters are the values of eccentric ratio in the direction of both X and Y. The X-axis is the direction of the input motion and Y-axis is perpendicular to the former, as shown in Figure 1 a). The eccentric ratio of 0.0, 0.15 and 0.30 were applied in X direction and those of 0.0 and 0.15 were applied in Y direction. Here, the eccentric ratio R_e is defined as a function of distance between the center of gravity and rigidity as shown in Eq.1, which is prescribed in the Building Standard Low Enforcement Order of Japan, and represents how easily a structure can vibrate torsionally [3].

$$R_e = \frac{e}{r_e} \qquad \text{Eq.1}$$

e : Eccentric Distance.
i.e. Distance between the center of gravity and rigidity.

r_e : Radius of Spring Force.

$$r_{ex} = \sqrt{K_R / K_x}$$

$$r_{ey} = \sqrt{K_R / K_y}$$

K_R : Torsional Stiffness.

K_x, K_y : Horizontal Stiffness to The Direction of X and Y.

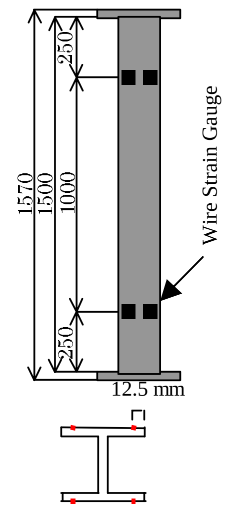


Figure 2 Strain Gauges on Column

In structural design of building with eccentric ratio *Re* larger than 0.15, design external force should be made to increase up to 1.5 times in accordance with the values of eccentric ratio. An eccentric ratio of zero means that the structure has no eccentricity. The number of specimens is eight as shown in Table 3 with the test parameters; three were prepared for the PSD tests (P00, P1M15 and P1M30) and two with eccentricity in the both directions (P2M1515 and P2M3015). In addition, three specimens (S00, S1M15 and S1M30) were used for the shaking table tests in order to compare the reproduced behaviors between the PSD test and those of the shaking table tests. In order to achieve the specific eccentricity, columns were shifted by the distance shown in Table 3 from the location for the structure without eccentricity.

Scale Factor

The test structure was assumed to be 1/2-scaled model of a real size structure. However, an actual prototype structure in real size did not exist because the main purpose of this research was to investigate the basic effect of the torsional response on structural damages, not to observe the response of a specific structure. Because of this, the horizontal strength of column was assumed simply to be proportional to the area of section. Scale factors for each item are listed in Table 4 [4]. Single underlined items are the items that cannot be scaled down, and double underlined items are the items of which scale factor does not have proper relationship with the real size structure.

Measurement

Strain gauges put on the flange at both ends of columns measured the strains of it as shown in Figure 2 (black rectangular marks show strain gauge locations). Four strain gauges were put at one end, eight gauges were used for one column, and then total 64 strains at different points were measured during the PSD and the shaking table tests.

Three displacement transducers were used to measure response bi-directional horizontal displacement and rotational angle of each floor as shown in Figure 1 b). Two transducers were for X direction and rotation, and one was for Y direction. Two additional transducers measured the slip displacement at bottom of basement during the shaking table tests.

Three accelerometers were used to measure response acceleration during each floor at the shaking table test. Two were for Y direction and rotation, and one was for X direction. One accelerometer was placed on the center of the basement to measure actual input motion to a specimen.

Table 3 Names of Specimens and Test Parameters

		Eccentric Ratio in Y direction		
		0.00		0.15
		Shaking Table Test	Pseudo Dynamic Test	
Eccentric Ratio in X direction	0.00	S00 (0, 0)	P00 (0, 0)	------
	0.15	S1M15 (0, 310)	P1M15 (0, 310)	P2M1515 (490, 290)
	0.30	S1M30 (0, 560)	P1M30 (0, 560)	P2M3015 (440, 520)

(x , y) : shifted distance from uniform arrange in X and Y direction

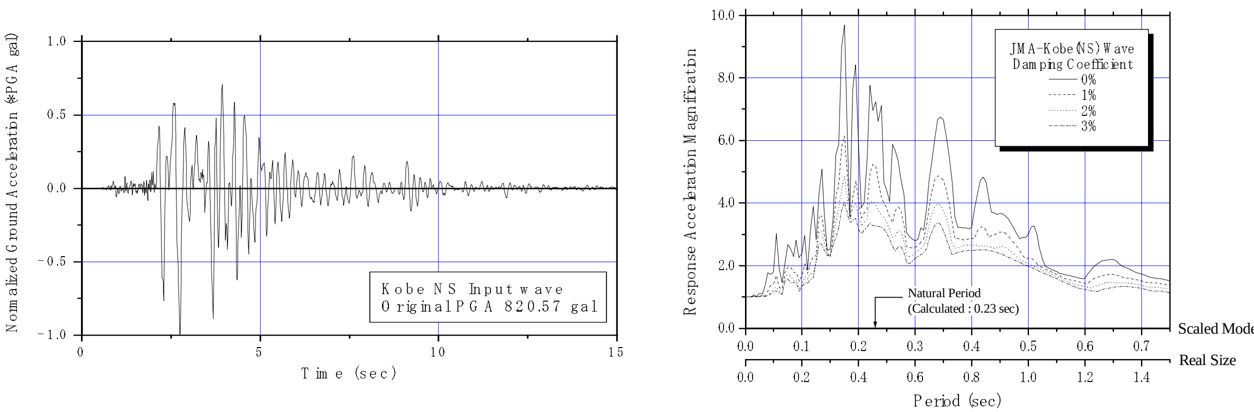
Table 4 Scale Factors

Physical Phenomena			
Length	1/2	Area	1/4
Volume	1/8	<u>Gravity Acceleration</u>	1.0
Specific gravity	1.0	Mass	1/8
Rotational inertia	1/32	Time	1/2
Column			
<u>Young's modulus</u>	1.0	Axial strain	1.0
<u>Curvature</u>	2.0	<u>Twisting strain</u>	2.0
Horizontal strength	1/4	Horizontal stiffness	1/2
Yield deformation	1/2	Rotational stiffness	1/8
Response of Structure			
Natural period	1/2	Horizontal acceleration	2.0
Horizontal velocity	1.0	Horizontal deformation	1/2
Rotational acceleration	1.0	Rotational velocity	1.0
Rotational deformation	1.0		

Single Underlined Item : Item that cannot be scaled down
Double Underlined Item : Item of which scale factor does not have proper relationship with the real size structure

INPUT MOTIONS

The North-South component of JMA-Kobe (Kobe Observatory of Japan Meteorological Agency) recorded at the Hyogo-Ken-Nanbu earthquake in 1995 was used for the input motion, of which time axis was scaled down by 1/2 according to the scale factor. The input earthquake wave and the response acceleration magnification with various damping coefficient are shown in Figure 3. Five different normalized peak acceleration waves of 2.0, 4.5, 9.0, 16.4 and 24.0 m/sec^2 were inputted in order of level. Peak accelerations in a real size are 1.0, 2.25, 4.5, 8.2 and 12.0 m/sec^2 because of scale factors. The shaking table tests were conducted with these input motions prior to the PSD tests and recorded acceleration at the basement of each specimen was used for the input motion to the PSD tests. In the PSD tests on P2M1515 and P2M3015, the acceleration record at S00 was used for the input motion with 10 degrees rotated from X direction of them. It means that the magnification are 0.985 (= cos10°) and 0.174 (=sin10°) in X and Y direction, respectively. Those magnifications were determined by the pre-loading tests taking account of the strength characteristics of H-shaped steel column.



a) Earthquake Acceleration **b) Response Acceleration Magnification**

Figure 3 Input Acceleration Wave

TEST RESULTS

Fundamental Characteristics of Specimens

In order to measure the natural periods and damping coefficients of specimens, the responses with the white noise input were measured at the shaking table tests. On the other hand, since a stiffness matrix was needed for the PSD tests to assume a damping matrix, unit-loading tests, that small amounts of force was loaded at each floor and in each direction, were carried out just after setting up each specimen. Then, all deformations for each force were measured, and the flexibility matrix was generated. The natural periods were calculated with the flexibility matrix and the mass matrix for each specimen.

Table 5 Natural Periods of Specimens

Specimen	Natural Period (sec)		
	X Direction	Y Direction	Torsion
S00	0.260	0.410	0.220
S1M15	0.280	0.410	0.240
S1M30	0.280	0.410	0.250
P00	0.264	0.401	0.201
P1M15	0.264	0.390	0.217
P1M30	0.276	0.393	0.226
P2M1515	0.279	0.412	0.230
P2M3015	0.280	0.416	0.239

Measured natural periods were listed in Table 5. The natural periods of the specimens in both X and Y direction of the shaking table and the PSD tests are almost the same, however, those of torsional response are a little different. It means that the specimens employed in the tests had almost the same fundamental characteristics. Since the natural periods of the shaking table tests were calculated with transfer function at the white noise input, the accuracy of the natural period of the torsional response is not so high because it is higher modes.

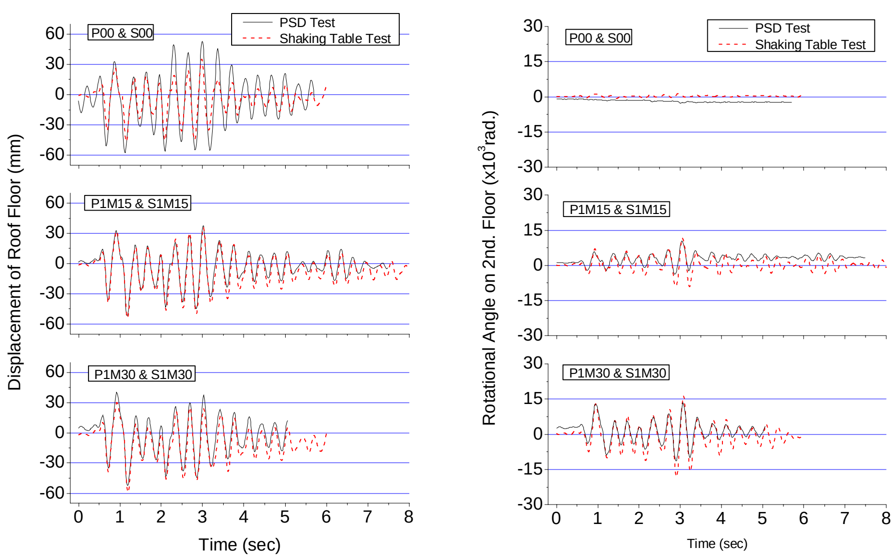
The damping coefficients could be assumed as 1% from the shaking table test with white noise input, and its value was used for the proportional damping coefficients to the initial stiffness in the PSD tests.

Comparison of Results of PSD Tests and Shaking Table Tests

Responses of Specimens

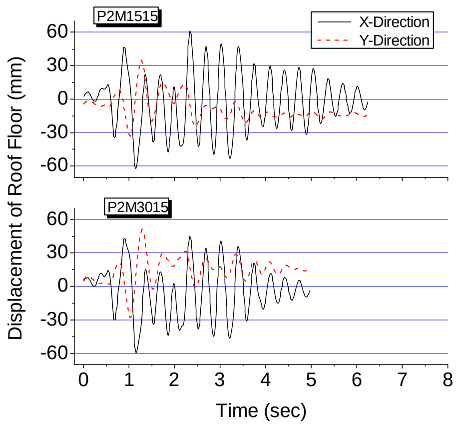
The response displacements at the center of gravity on roof floor in the X direction and rotational angles of the first story of which the input level was 16.4 m/sec^2, are shown in Figure4. In the figure, solid lines show the results of the PSD tests and broken lines are those of the shaking table tests. The response displacements of P1M15 and P1M30 agreed very well with those of the shaking table tests, which include maximum response displacements. Moreover, the rotational angles of those specimens show rather well correspondence as wall. However, the response displacement of P00 was evidently larger than that of S00, the behaviors of both did not coincide. From Figure 4, the maximum response displacements at the center of gravity of employed specimens are almost in agreement, in spite of difference of eccentric ratios. Meanwhile the response rotational angles of specimens with eccentricity grow with increasing of eccentric ratio, as against those of P00 and S00 are very small. It was observed that the eccentricity of specimen inclined to have an influence on the rotational response.

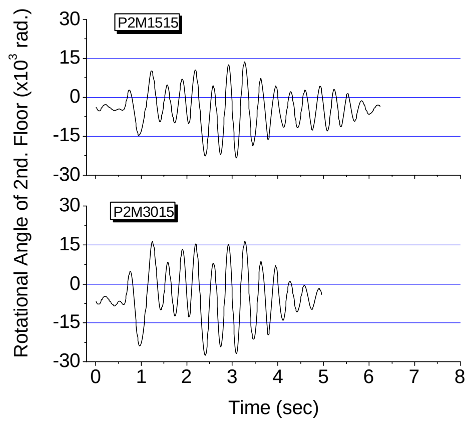
The response displacements of P2M1515 and P2M3015 in X direction are a little larger than that of P00, and the responses in Y direction are conspicuous. The response of each direction vibrated separately with the individual natural periods, i.e., X and Y direction, therefore the times at maximum response did not coincide.



a) Displacement of P00, P1M15, P1M30 (Roof Floor) **b) Rotational Angle P00, P1M15, P1M30 (First Story)**

Figure 4 Dynamic Responses of Specimens (16.4 m/sec^2 Input Tests)





c) Displacement of P2M1515, P2M3015 (Roof Floor) **d) Rotational Angle of P2M1515, P2M3015 (First Story)**

Figure 4 Dynamic Responses of Specimens (16.4 m/sec^2 Input Tests) (continued)

Hysteresis Loops

The relationship between story shear force and inter-story drift in the first story of the PSD test specimens for the same input level are compared with those of the shaking table tests in Figure 5. Though the behaviors of P1M15 and P1M30 agreed well with those of the shaking table tests, the result of P00 was different from that of S00, especially the initial stiffness of the shaking table test was a little higher than that of the PSD test. Because of the difference of stiffness, the response of the PSD test did not agree with that of the shaking table test. The reason why the stiffness of S00 and P00 were different needs further investigation. From these results, it will be said that the PSD test can adequately reproduce the dynamic response of specimen, if the stiffness of specimens agree with each other.

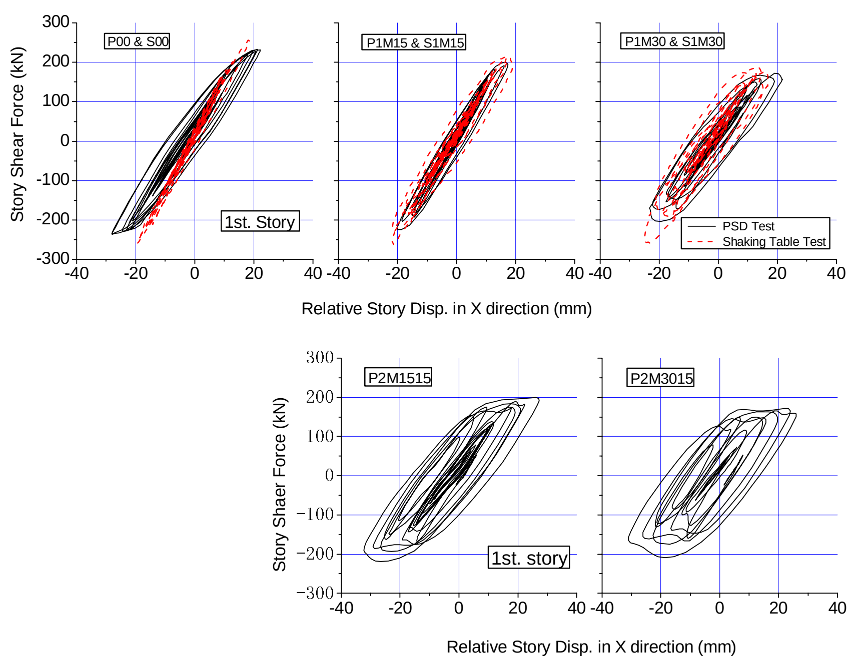


Figure 5 Story Shear Force and Story Drift Relationship (16.4 m/sec^2 Input Test)

The hysteresis loops of P2M1515 and P2M3015 are larger than those of specimens with uni-axial eccentricity; it means that the influence by yielding of columns in Y direction make the response of X direction larger even in the same input level test.

Figure 6 indicates the orbits at the center of gravity in the first story of the PSD tests. The results of P1M15 and P1M30 show drifts in Y direction, it is understood that the effects of eccentricity promote the deflection of perpendicular direction where input motions were not given. As a logical outcome, the orbits of P2M1515 and P2M3015 show large drift in both directions.

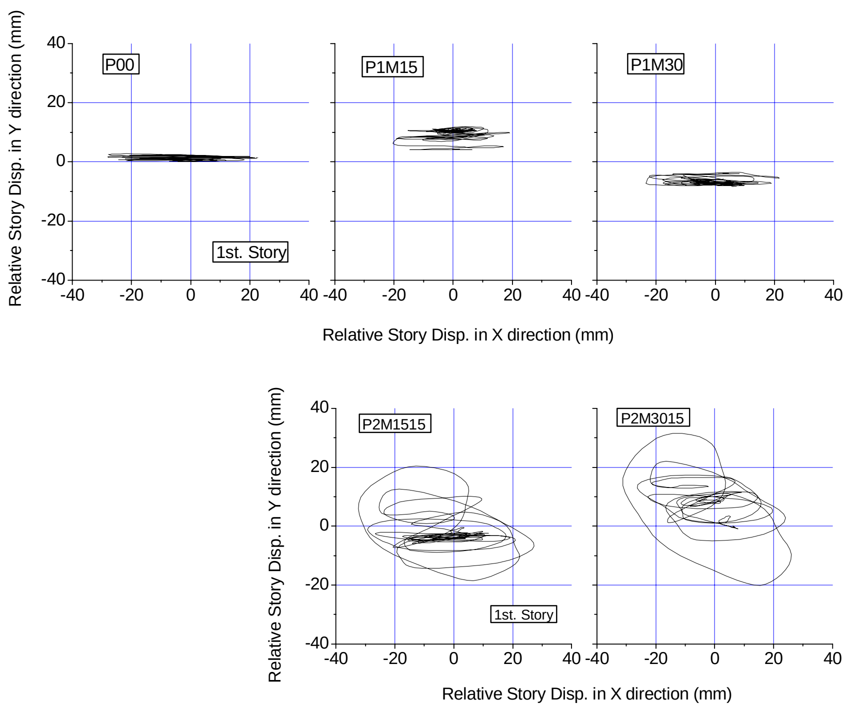
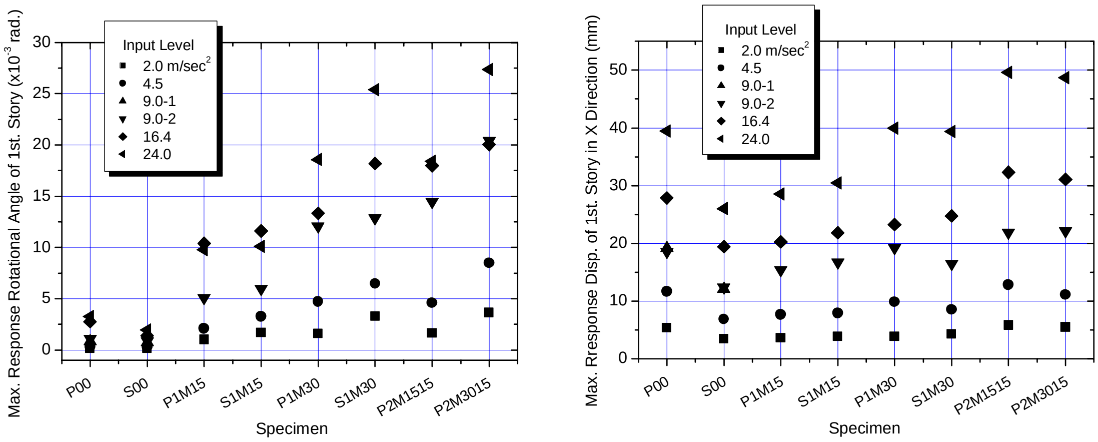


Figure 6 Orbits of The Center of Gravity of PSD Specimens (16.4 m/sec^2 Input Test)

Maximum Responses

Figure 7 a) shows maximum response displacements at the center of gravity of the first story in the X direction for each input level test. As mentioned before, P00 and S00 are quite different especially for relatively large input levels. P1M15 and P1M30 agree well with S1M15 and S1M30 regardless of input level. It can be seen that there is the tendency to slightly increase the maximum response displacement at the center of gravity with increasing of the eccentric ratio. Figure 7b) shows maximum torsional response angle of the first story for each input level test. The maximum torsional response angle of P1M30 at input level of 16.4 m/sec^2 was 28% smaller than that of S1M30. The maximum torsional response angle is the relative angle to the basement and residual torsional angle could be accumulated. The maximum angle of P1M30 at input level of 24.0 m/sec^2 was also 27% smaller than that of S1M30. Maximum torsional response angle increased according to the eccentric ratio. For example, the ratio of maximum angle of P1M30 to that of P1M15 at input level of 16.4 m/sec^2 was 1.15.



a) Displacement of First Story **b) Torsional Angle of First Story**

Figure 7 Comparisons of Maximum Responses

Responses of Individual Columns

Since the tendency of promoting torsional vibration by eccentricity of specimen was observed as mentioned above, the responses of individual columns are indicated below. Figure 8 shows the response displacement of eccentric and non-eccentric bays with those at the center of gravity of P1M30 at the input test of 16.4 m/sec^2. The displacement of eccentric bay are larger than that of the center of gravity, on the other hand the one of non-eccentric bay show opposite trend. The ratio of maximum response of eccentric bay to that at the center of gravity was about 1.4; the one of non-eccentric bay was 0.6. These outcomes make clear that the eccentric bay is forced to be deformed largely, in spite of the displacements at the center of gravity of specimens were not as different as shown in Figure 4 a).

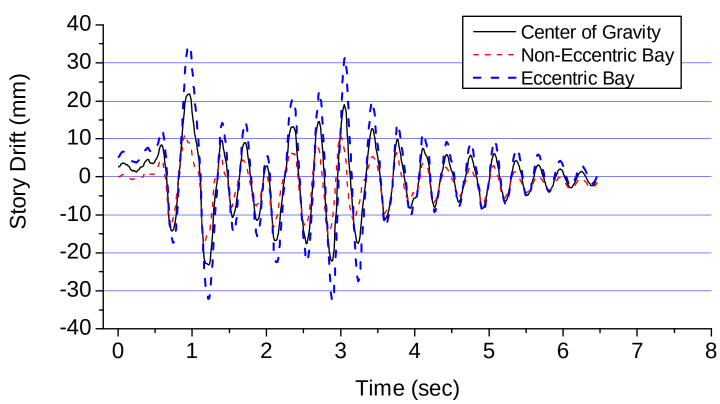
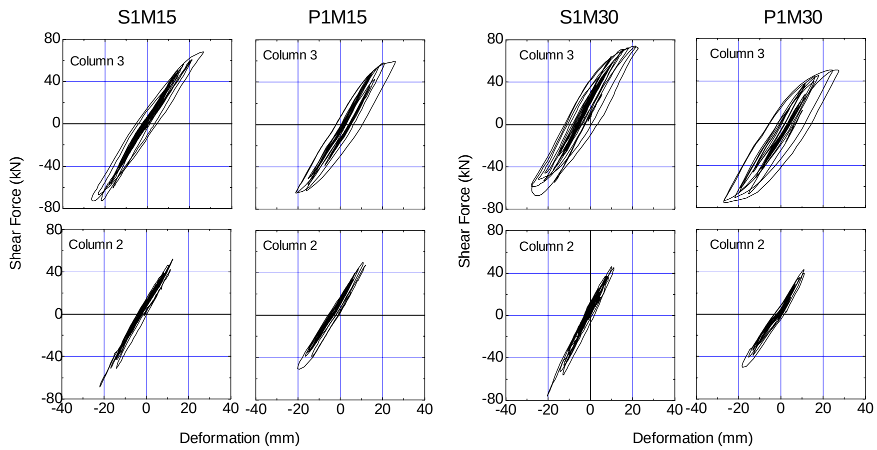


Figure 8 Comparison of Displacement Response in Each Street of Specimen
(First Story of P1M30, 16.4 m/sec^2 Input Test)

The restoring characteristics of individual columns in the first story of specimens with eccentricity are illustrated in Figure 9. Here, Column 2 is in non-eccentric bay and Column 3 is in eccentric bay as shown in Figure 1 a). The abscissa of the graph is deformation of column and the ordinate shows shear force obtained from measured strain of column. The restoring characteristics of the PSD and the shaking table tests adequately agreed with each other, it is confirmed that the both results correspond in the level of structural elements. The Columns 3 have a spindle-shaped hysteresis loops, it means that the columns had been yielded and reached in plastic range. On the other hand, the Columns 2 show elastic restoring characteristics, those had remained in elastic range. The phenomena which areas of hysteresis loops of P1M30 and S1M30 are larger than those of P1M15 and S1M15, show the possibility that structural element in eccentric bay will be suffered heavy damage in large earthquake excitations.



a) Eccentric Ratio 0.15 b) Eccentric Ratio 0.30

Figure 9 Restoring Characteristics of Individual Columns in First Story (16.4 m/sec^2 Input Test)

ANALYTICAL STUDIES AND DISCUSSIONS

Analytical Method

In order to verify the PSD test results, a series of nonlinear analyses [5] were executed. Figure 10 indicates a schematic model for the specimen and details of column element employed in the analytical studies. The mass of each slab was distributed in five positions, as the rotational inertia was equal to the one of the specimen. The slabs of each floor were assumed rigid. A multi spring model that can adequately represent the axial and bending characteristics of structural element was adopted for H-shaped steel column, coupling with bi-axial shear and torsional spring models. The restoring characteristic of the multi spring model was the Ramberg-Osgood model, of which parameters were derived from the test results of P00. The property of models includes the effect of strain hardening but does not the one of strain rate. The other conditions of the analyses were same as the PSD test, i.e., integration method, input accelerations, damping factor, etc.

A considerable thing was a degree of fixing at the bottom of the first story columns. The end plates of columns were set up on a steel foundation, and then the degree of fixing was lower than those of other columns that were fixed on the rigid thick RC slabs. So the degree of fixing of the first story columns were determined by making the natural period of analytical model in X direction agree with the one of P00 specimen.

The natural periods of each specimen obtained from the analyses almost agree with the PSD test results, as shown in Table 6, even though a tendency that the difference of both becomes rather large with increasing of the eccentricity ratio is observed.

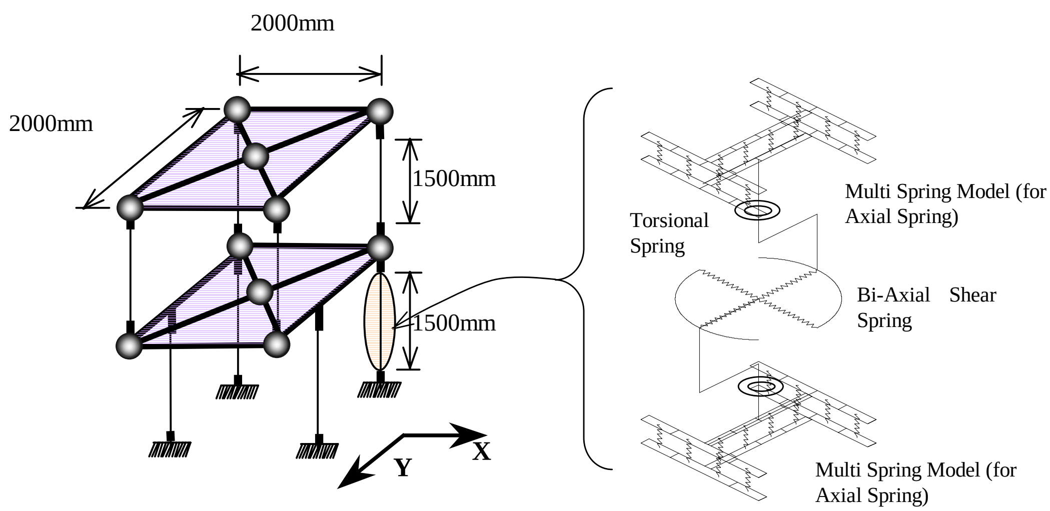


Figure 10 Analytical Models for the Specimen

Table 6 Comparisons of Natural Periods between Analyses and Experiments

Name of Analysis	Natural Period of X direction (sec)		
	Analysis	PSD Test	Ratio (Test / Ana.)
A00	0.264	0.264	1.00
A1M15	0.270	0.264	0.98
A1M30	0.289	0.276	0.96
A2M1515	0.276	0.279	1.01
A2M3015	0.298	0.280	0.94

Analytical Results

Dynamic Responses

Figure 11 shows the story shear force and story drift relationships of each specimen in 16.4 m/sec^2 input obtained from the analyses in comparison with the test results. The analytical results are generally larger than those of the PSD tests, and they do not show always-good agreement. The magnifications of energy dissipation of the analytical results to those of the PSD tests are 1.00(P00), 1.75(P1M15), 0.78(P1M30), 0.85(P2M1515) and 1.85(P2M3015), respectively.

The displacement responses of each analytical study are also larger than the PSD tests as shown in Figure 12. Though the differences of displacement appear after the peak response, the period obtained from the analyses can adequately reproduce those of the specimens.

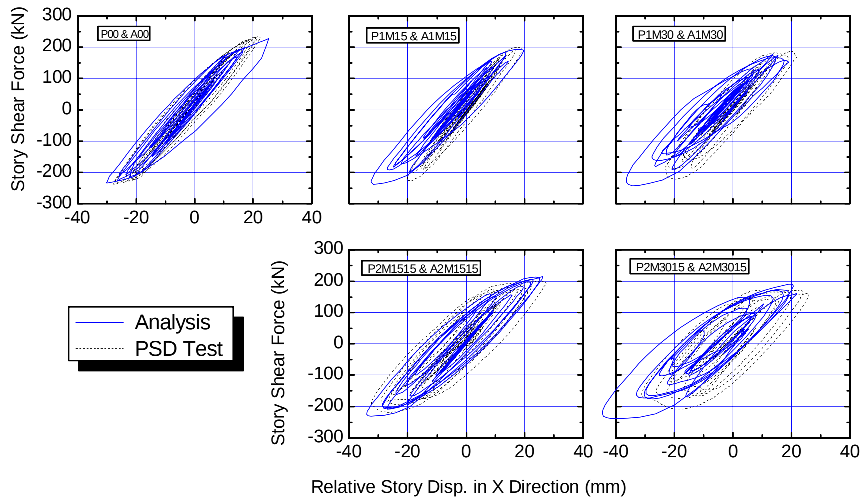


Figure 11 Comparisons of Base Shear Force and Story Drift Relationship of First Story (16.4 m/sec^2 Input Test)

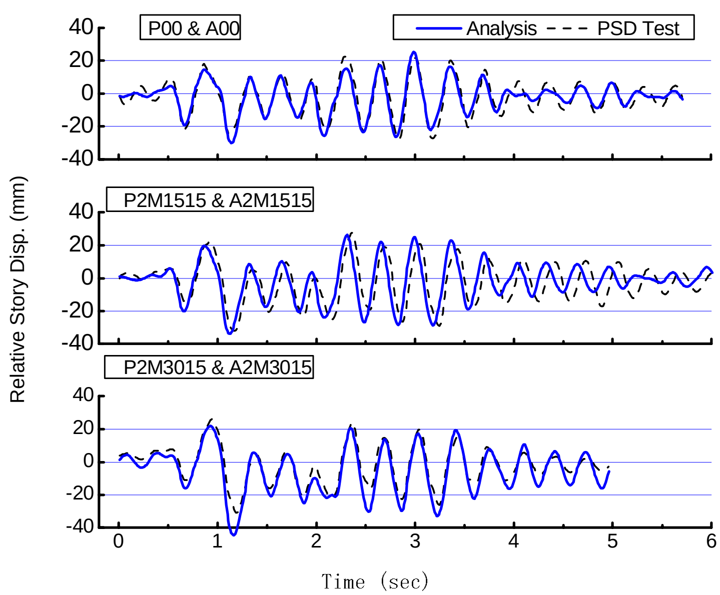
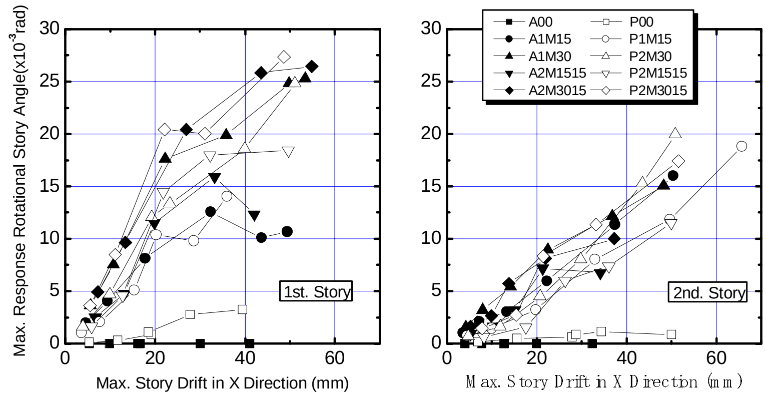


Figure 12 Comparisons of Displacement Responses of First Story (16.4 m/sec^2 Input Test)

Maximum Responses

The relationship between maximum displacement and maximum rotational angle obtained from the each PSD tests and analyses are plotted in Figure 13. Here, white marks show the PSD test and black marks are analytical results. From Figure 13(b), the rotational responses exist even in second story, which has no eccentricity. It can be seen that there are almost linear relationship between the rotational and displacement response. The tendency is a characteristic common to all in the experimental and the analytical results.



a) First Story **b) Second Story**

Figure 13 Maximum Responses of Each Specimen (PSD Tests and Analyses)

CONCLUDING REMARKS

A series of PSD tests on the specimens with various eccentricities were conducted in order to investigate the mechanism of damage due to torsional response. In addition, the shaking table tests on the same specimens had inspected the validity of the PSD test method. Furthermore, the analytical studies to compare with the PSD tests results were carried out. The outcomes from these experimental and analytical studies are summarized as follows;

1. The pseudo dynamic test method with torsional response was newly developed. If the stiffness of specimen can be given properly, the pseudo dynamic test can reproduce the dynamic response of eccentric specimen with sufficient accuracy.
2. The displacement response at the center of gravity of specimens was not so influenced by the values of eccentric ratio; however, the torsional response angle increases evidently according to the eccentric ratio.
3. There is the possibility that structural elements in eccentric bay will be suffered heavy damage in sever earthquake excitations.
4. The nonlinear analyses can roughly reproduce the response of the PSD test, though the responses of analyses were rather larger than the latter.
5. The maximum rotational response and displacement response has a correlation, which is almost linear in the results obtained from this study.

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REFERENCES

1. Kato H, Fukuta T, Kusunoki K, Kumazawa F, Hirosaki Y. "Experimental study on torsional seismic behavior of steel frame specimen with eccentricity." Journal of Constructional Steel, Vol.9, 2001; 389-396. (in Japanese)
2. Kumazawa F, Fukuta T, Kato H, Kusunoki K, Hirosaki Y. "Study on torsional seismic behavior of steel frame specimen with uni- and bi-axial eccentricity." Journal of Constructional Steel, Vol.10, 2002; 383-390. (in Japanese)
3. "Guideline for the code and orders related to building structures." Building Center of Japan, 2001. (in Japanese)
4. Kumazawa F. "Study on response characteristics of small scaled reinforced concrete structures." Ph. D Thesis, University of Tokyo, 1996. (in Japanese)
5. Kozo System, Inc. "SNAP (Structure Non-linear Analysis Program), Ver.2", Japan